BASS IN CONCERT HALLS – RECENT STUDIES ON THE SEAT-DIP EFFECT

H Tahvanainen Department of Computer Science, Aalto University School of Science, Finland
T Lokki Department of Computer Science, Aalto University School of Science, Finland

1 INTRODUCTION

The seat-dip effect is collectively referred to as the phenomena where the direct sound and its delayed copies starting after 5-7 ms interfere destructively leading to low frequency attenuation[8,15,16,18]. The delayed copies occur when the direct sound travels at grazing angles over the plane formed by the tops of the seat backs (or shoulders in occupied halls[18]). The sound then bends between the seats, and reflects off the floor. At the receiver, this delayed copy joins the direct sound resulting in destructive interference being half-wavelength apart at certain frequency. In addition, delayed copies of the direct sound occur with diffraction from the tops of the seat backs. The main attenuation lies between 100-300 Hz, where its wavelength corresponds to four times the height of the seat backrest. The attenuation can extend up 1 kHz and it can be as deep as 15-20 dB.

A rich bass and warmth are considered to be perceptually interchangeable terms[4,14]. In addition, bass is often clustered with fullness, depth and richness in listening tests using individual vocabulary profiling[11]. Hence, a loss of low frequencies in the direct sound caused by the seat-dip effect might be considered hazardous for the sound quality in concert halls. For example, Barron and Marshall observed that spatial impression is reduced if the early reflections also suffer from the seat-dip effect[3].

Most research on the seat-dip effect, for example related to the elimination of the effect, starts from the premise that such attenuation in the direct sound is detrimental to perception of sound quality in concert halls. Many methods focus on total elimination of the effect[1,7,8] or at least on shifting it to a lower frequency[15] – an approach often justified by the insensitivity of human hearing to low frequencies. However, for example intimacy seems to require pronounced bass below 100 Hz[12] meaning that this approach may not be beneficial after all. Furthermore, there is some evidence that if the later sound contains the low frequencies missing from the direct sound, the perception of bass might be enhanced[21].

2 MEASUREMENTS OF THE SEAT-DIP EFFECT WITH LOUDSPEAKER ORCHESTRA

Most of the existing measurement and analysis data on the seat-dip effect is captured by using one or a few sources on stage. To address this issue, twelve concert halls in Central Europe and Finland were measured with a loudspeaker orchestra and analysed with time-frequency and spatiotemporal methods[18]. Summing several source positions on stage diminishes the seat-to-seat variance of the seat-dip effect, and may thus yield perceptually more relevant results, as real concerts involve more than one source. Figure 1 illustrates that with individual sources the seat-dip effect is sensitive to the source position on stage. The figure shows the development of the magnitude and the frequency of the spectrum minimum in 1 ms time window increments, i.e., the development of the maximum seat-dip attenuation. The behaviour of the maximum attenuation with single sources depends quite strongly on the source position, and it is not as smooth as that of the summed sources. Especially the

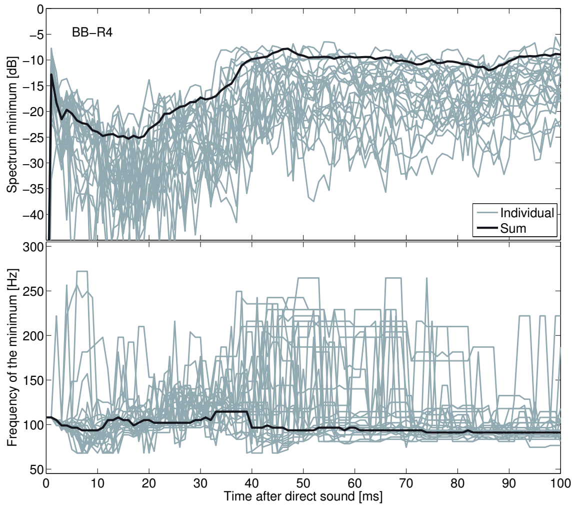

Figure 1 The difference between measuring the seat-dip effect with individual sources (grey curves) and with sources summed (black curve) at 1-ms increments after the direct sound in Palais de Beaux-Arts, Brussels (BB) at receiver position R4 (19 meters from the stage). The plot on the top shows the magnitude of the spectrum minimum and the bottom plot shows the frequency at which the minimum occurs. The frequency responses were 1/12-octave smoothed.

frequency of the spectrum minimum seems to follow no particular trend with single sources, but with the full loudspeaker orchestra the minimum frequency is rather stable.

Figure 2 shows the development of both the frequency and magnitude of the spectrum minimum grouped by hall type. In this case, it also means grouping by flat floor and open seats vs. raked floor and closed seats. R1-R5 described different receiver positions with increasing source-receiver distance (7 to 23 metres). It can be seen that the frequency of the spectrum minimum changes abruptly after 5-9 ms, meaning that the seat-dip attenuation takes effect. Furthermore, the minimum of the spectral minimum is typically reached earlier in the shoebox halls (around 10 ms) than in the non-shoebox halls (around 20 ms). The shoebox halls also have a deeper spectrum minimum, but it decreases more rapidly in time than in the non-shoebox halls. In addition, the frequency of the spectrum minimum remains almost constant in time in the non-shoebox halls, while it varies more in the shoebox-halls. This results most likely from the open seats in the shoebox halls that provide more paths of different lengths for the diffracted sound and thus yield frequency-varying attenuation.

In the analysis of the time-frequency development of the concert halls two different seat-dip attenuation types emerge, depending on the abovementioned grouping of floor and seat types (see Figure 3). The seat-dip attenuation is narrow-band in halls where the floor is raked, and the seat backs extend to the floor (closed seats). These halls are mostly fan- and vineyard-shaped halls. In the halls where the floor is flat and the seat backs leave some space below the seat (open seats, seats with underpass), the attenuation of the direct sound extends to a wider frequency range. These are mostly shoebox halls.

Ishida[9] proposed that the maximum attenuation frequency is caused by the interference of direct sound and the sound that is first diffracted from the seat top and then either (1) reflected off the floor when the seat backrest extends all the way to the floor, or (2) reflected off the seat bottom in the case of the seat with an underpass. Since, the path length of the interfering sound should be 1/2 wavelength of the maximum attenuation frequency, the seat backrest height thus corresponds to a quarter wavelength of the maximum attenuation frequency. As the height of the seat backrest is smaller for the open seats than for closed seats, the maximum attenuation frequency is lower (at around 100 Hz) in the non-shoebox halls than in the shoebox halls (at around 200 Hz).

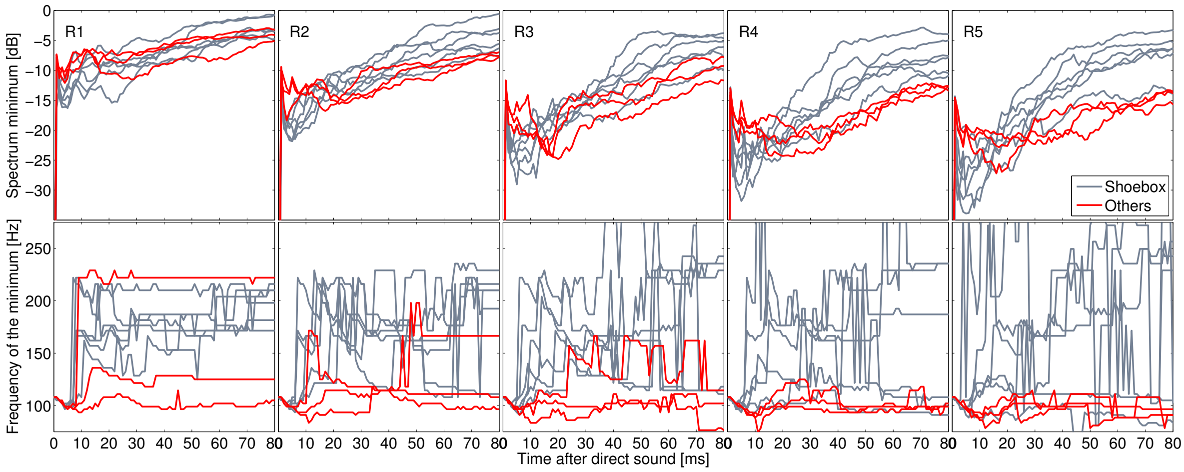

Figure 2 The spectrum minimum and its frequency at 1-ms time increments up to 80 ms after the direct sound in the shoebox vs. non-shoebox halls at different receiver positions. The plot on the top shows the magnitude of the spectrum minimum and the bottom plot shows the frequency at which the minimum occurs. The frequency responses were 1/12-octave smoothed.

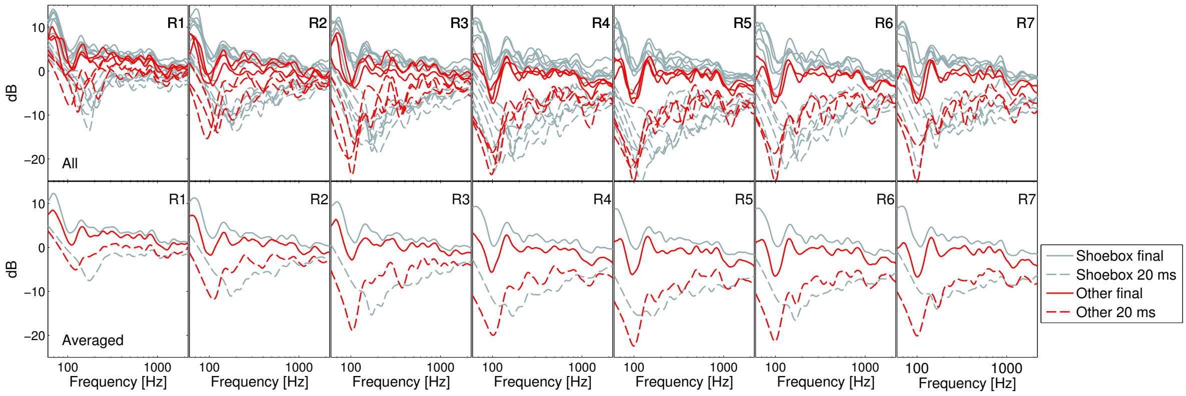

Figure 3 The 20-ms and final frequency responses of shoebox vs. non-shoebox halls at different receiver positions. The plots on the top row show all the responses, and the plots on the bottom row show the averages of the two categories. The shoebox halls contain six halls and the non-shoebox halls three.

The difference in the attenuation bandwidths between the hall types arises from the combination of the seat and the floor design. The seats with underpasses yield numerous diffraction paths with different lengths, which generate a wide frequency band for the attenuation. A flat floor also contributes to the wide attenuation band, as the diffracted sound from preceding seat backrest arrives at a grazing angle to the consecutive seat backrests. On the other hand, closed seats provide only paths that are multiples of the seat back rest height. This combined with a raked floor where the seat diffraction is directed more upwards rather than towards the consecutive tops of the seat backrests, generates a narrow attenuation band.

The early reflections arriving at non-grazing incident angles to the seats may correct the seat-dip attenuation, i.e., to yield a flatter frequency response[8]. The analysis of the spatiotemporal plots of the twelve concert halls shows that the late early reflections between 30-120 ms arriving from the upper hemisphere appear to be beneficial for this objective correction. These reflections and the overall accumulative sound energy differ substantially across halls due to geometrical differences. In most shoebox halls, the full frequency response bears no trace of the seat-dip attenuation, while in the other halls, the full frequency response can be characterised with the same lack of bass as the direct sound.

Of course, the subjective sensation of bass cannot directly be deduced from the temporal or spatial development of the frequency response. According to Bradley and Soulodre[6], the perceived level of bass is more influenced by the late sound (after 80 ms) than the early sound. Even if the the early bass level was low, high level of late bass sound would improve the perceived level of bass. Kahle[10] also suggested that sound energy arriving between 80-160 ms correlates well with the perceived level of bass. However, increasing reverberation time at low frequencies does not seem to enhance perception of bass[6]. At the same time, if the early reflections preserve the temporal envelope of the sound (i.e., they come from hard flat surfaces), and they arrive from lateral directions, they are perceived to have a stronger bass than if they arrive from median directions[13]. Consequently, contrary to what had previously been proposed[5], ceiling reflections alone might not compensate the seat-dip effect from the perceptual point of view.

3 PERCEPTION OF BASS-REGISTER INSTRUMENTS IN THE PRESENCE OF THE SEAT-DIP EFFECT

Orchestral instruments that have their tuning range within the seat-dip attenuation range, such as double bass, tuba, trombone, timpani, bassoon, and cello, may lack bass and articulation due to the seat-dip effect. When the attenuation is a narrow dip centred around 100 Hz, mostly the fundamentals of these instruments are missing in the direct sound. When the attenuation starts at mid-low frequencies (above 200 Hz) and spans a wider frequency range, mostly the second, third and also higher harmonics are missing in the direct sound. Depending on the time-frequency development of the sound energy in the concert hall, these missing harmonics may arrive later with the reflections. For example, it can be said that the mid-low frequencies are delayed in the shoebox halls due to the seat-dip effect. This can lead to masking effects when the bass-register instruments accompany mid- and treble register instruments, especially because the fundamentals of the bass-register instruments tend to radiate weakly due to the mismatch between the wavelength of the fundamental and the size of the instrument[2].

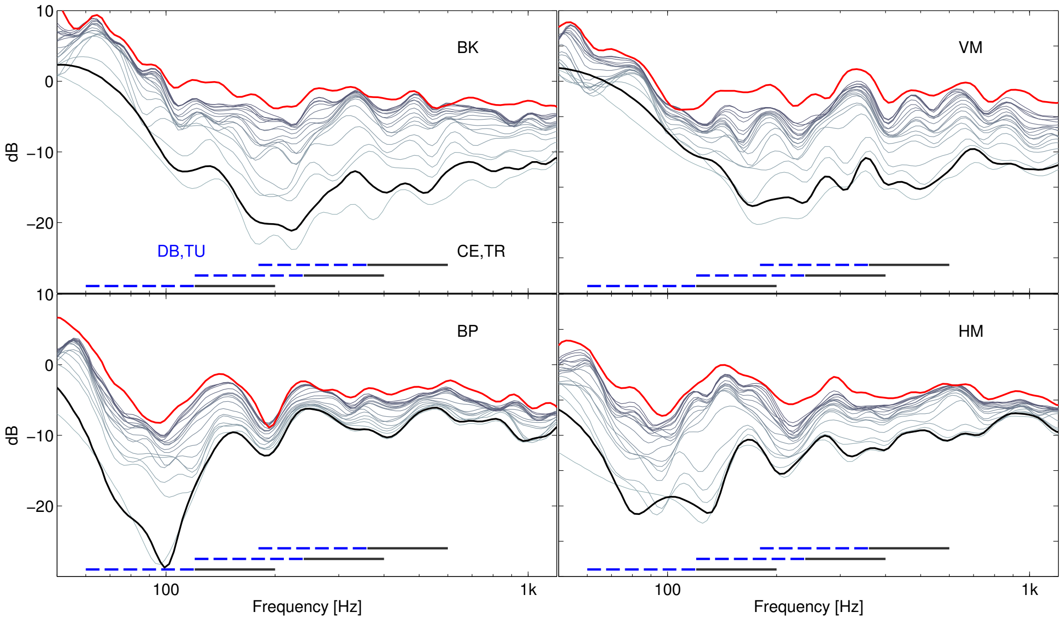

Figure 4 Time-frequency development of the concert halls measured at 19 meters from the stage. One-third octave smoothing has been applied. The tuba (TU) and double bass (DB) range (60-120 Hz) is marked with a dashed line underneath the curves. The cello (CE) and trombone (TR) range (120-350 Hz) is marked with a solid line. The three levels of the lines indicate the fundamental, second, and third partial, respectively.

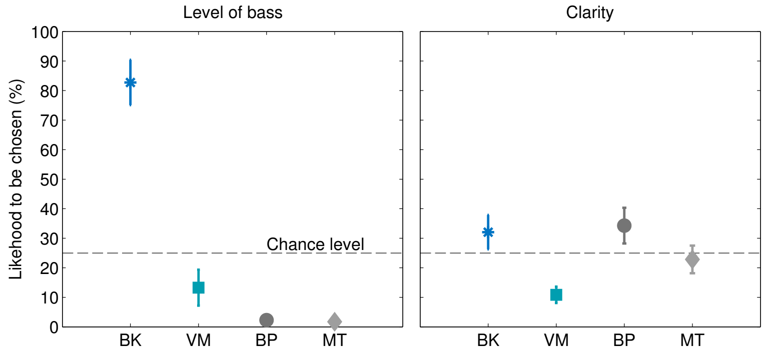

Figure 5 The probablity of the concert halls to be chosen to have the highest level of bass and the highest clarity with short musical excerpts. The concert halls are Berlin Konzerthaus (BK), and Vienna Musikverein (VM) - and two vineyard halls: Berlin Philharmonie (BP), and Helsinki Music Centre (HM), and the listening position is 19 meters from the stage (R4).

An example of the possible masking is indicated in a recent online listening test studying the timing between different orchestra instrument groups[17]. It appears that in the Amsterdam Concertgebauw, which is a shoebox hall where the mid-low frequencies are missing in the direct sound, it is beneficial that the bass-register instrument play before the high-register instruments. By advancing the bass-register instruments, the second and third partials that fall to the seat-dip attenuation range, arrive before the fundamentals of the higher register instruments. Otherwise, these fundamentals could mask the higher partials of the bass-register instruments.

Bradley had estimated that the seat-dip effect can take away as much as 6 dB of the double bass sound at the 200 Hz octave band and he considers this detrimental to bass. To address this issue, in recent listening test the level and quality (in terms of articulation) of bass were assessed with some bass-register instruments with different seat-dip effect conditions[19]. In the first part of the test (N=9 subjects), short musical excerpts with double bass, cello, tuba, and trombone were used, and in the second part (N=13), the stimulus contained random individual notes from one of the instrument at a selected frequency range. An anechoic loudspeaker orchestra was auralised in two shoebox halls: Berlin Konzerthaus (BK), and Vienna Musikverein (VM) - and two vineyard halls: Berlin Philharmonie (BP), and Helsinki Music Centre (HM). The time-frequency development of these concert halls as well as the frequency ranges of the first, second, and third harmonics of the selected instruments are shown in Figure 4.

Shoebox halls are generally characterised by strong bass[14], and also in this study bass is perceived louder in the shoebox halls that in the vineyard halls (see Figure 5 for short musical excerpts and Figure 6 for individual instruments and selected frequency ranges). In addition, articulation or clarity of bass is somewhat related to the level of bass, as one of the shoebox halls, BK, is also among two halls with highest clarity with short musical excerpts. It could be that lack of mid-low frequencies combined with moderate reverberation time in BK enhance the perception of the clarity of bass. With individual notes, the vineyard halls are always considered the clearest, although with double bass at lower frequencies the results are not significant.

To conclude, as long as there are corrective reflections that contain the missing frequencies, the perception of bass is not hampered by the seat-dip effect. Namely, since the two vineyard halls are characterised with a lack of bass around 100 Hz in the direct, early, as well as the late sound, the study concurs the idea set forth by Schultz and Watters[15] that when the seat-dip attenuation frequency band is missing also in the reverberant sound field, the lack of bass is recognized. The suggested link between the level and clarity of bass in BK also points to the fact that a direct sound with some of the low-mid frequencies missing may render a clearer sound than a direct sound that contains this band. However, in general the perception of clarity of bass depends on the musical content: the instrument, its playing range, and playing style.

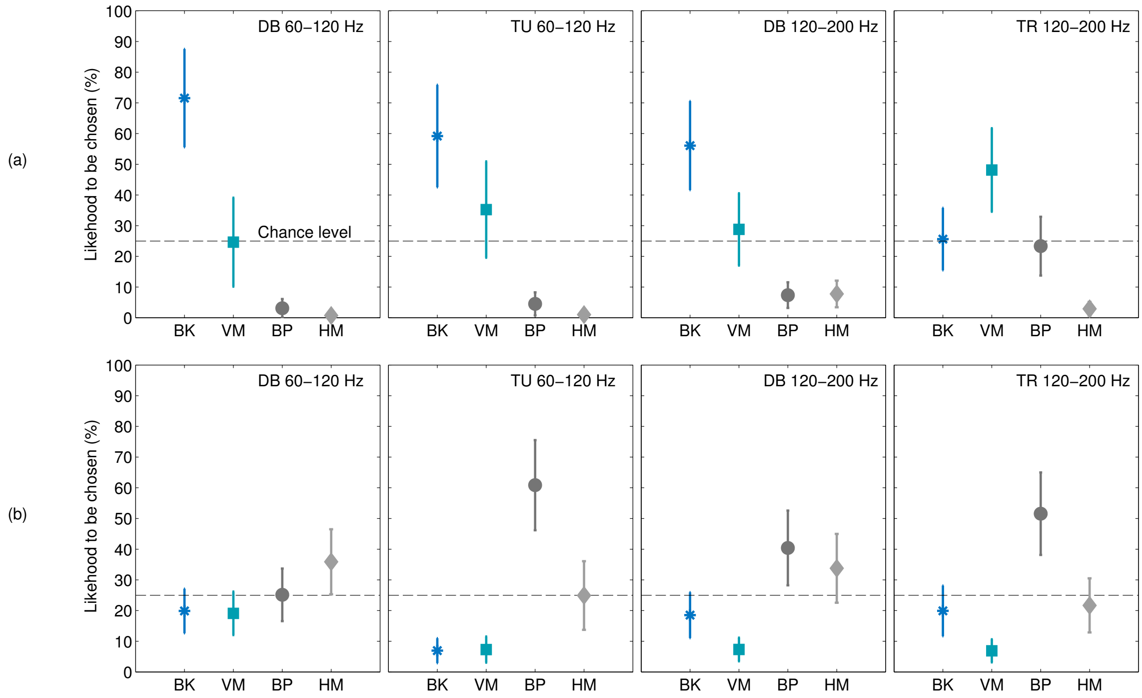

Figure 6 The probability of the concert halls to be chosen to have (a) the highest level of bass and (b) the highest clarity with different frequency ranges of double bass (DB), tuba (TB), and trombone (TR). The listening position is 19 meters from the stage (R4).

4 CONCLUSIONS AND FUTURE WORK

It appears that a direct sound with a wide band attenuation at mid-low frequencies is beneficial for the perception of bass. Furthermore, the attenuation can be controlled with the seat and floor design, but it is not yet verified which is the more prominent design element regarding the width of the attenuation. The results hint that it is not ideal to tune the seat-dip attenuation to a lower frequency, as the perception of bass may then be hampered.

At the same time, the geometry of the concert hall and the reflections that it provides are also important for the perception of bass. The late early reflections seem to compensate the lack of the low-frequency attenuation in the direct sound. However, it is not yet established whether the narrow-band low-frequency attenuation can be perceptually well compensated by later sound, as none of the measured concert halls had such time-frequency behaviour.

On a final note, there is still some ambiguity as to the mechanism of the seat-dip effect. Sessler and West[16] proposed that the vertical space between the seats acts as a resonator, and as an energy storing mechanism. Bradley[5] added that the horizontal space can also form a resonator. Takahashi[20] showed that the effect can at least qualitatively be predicted from scattering over a periodic structure when the seating area is considered as an absorptive layer over the rigid floor. It remains to be shown which mechanisms are more prominent.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the Academy of Finland, project no. [257099].

5 REFERENCES

1. Y. Ando, M. Takaishi, and K. Tada. Calculations of the sound transmission over theater seats and methods for its improvement in the low-frequency range. *Journal of the Acoustical Society of America*, 72(2):443–448, 1982.
2. A. Askenfelt. Eigenmodes and tone quality of the double bass. In *Dept for Speech, Music, and Hearing – Quarterly Progress and Status Report*, volume 23, pages 149–174, Roayl Institute of Technology, Stockholm, Sweden, 1982.
3. M. Barron and A. Marshall. Spatial impression due to early lateral reflections in concert halls: the derivation of a physical measure. *Journal of Sound and Vibration*, 77(2):211–232, 1981.
4. L. Beranek. *Concert Halls and Opera Houses: Music, Acoustics, and Architecture*. Springer- Verlag, New York, USA, 2nd edition, 2004.
5. J. Bradley. Some further investigations of the seat dip effect. *Journal of the Acoustical Society of America*, 90(1):324–333, 1991.
6. J. Bradley and G. Soulodre. Factors influencing the perception of bass. *Journal of the Acoustical Society of America*, 101:3135, 1997.
7. W. Davies and T. Cox. Reducing seat dip attenuation. *Journal of the Acoustical Society of America*, 108(5):443–448, 2000.
8. W. Davies, T. Cox, and Y. Lam. Subjective perception of seat dip attenuation. *Acta Acustica united with Acustica*, 82:784–792, 1996.
9. K. Ishida. Investigation of the fundamental mechanism of the seat-dip effect – Using measurements on a parallel barrier scale model. *Journal of the Acoustical Society of Japan (E)*, 16(2):105–114, 1995.
10. E. Kahle. *Validation d'un modéle objectif de la perception de la qualité acoustique dans un ensemble de salles de concerts et d'opéras*. PhD dissertation, Laboratoire d'Acoustique de l'Université du Maine, Le Mans, France, 1995.
11. T. Lokki, J. Pätynen, A. Kuusinen, and S. Tervo. Disentangling preference ratings of concert hall acoustics using subjective sensory profiles. *Journal of the Acoustical Society of America*, 132(5):3148–3161, November 2012.
12. T. Lokki, J. Pätynen, S. Tervo, A. Kuusinen, H.Tahvanainen, and A. Haapaniemi. The secret of the Musikverein and other shoebox concert halls. In *Proceedings of the IOA Auditorium Acoustics*, Paris, France, Oct 29-31, 2015.
13. T. Lokki, J. Pätynen, S. Tervo, S. Siltanen, and L. Savioja. Engaging concert hall acoustics is made up of temporal envelope preserving reflections. *Journal of the Acoustical Society of America Express Letters*, 129:EL223–EL228, 2011.
14. T. Schultz. Acoustics of the concert hall. *IEEE Spectrum Magazine*, 2(6):56–67, 1965.
15. T. Schultz and B. Watters. Propagation of sound across audience seating. *Journal of the Acoustical Society of America*, 36(5):885–896, 1964.
16. G. Sessler and J. West. Sound transmission over theatre seats. *Journal of the Acoustical Society of America*, 36(9):1725–1732, 1964.
17. H. Tahvanainen, A. Haapaniemi, J. Pätynen, and T. Lokki. Perceptual relevance of asynchrony between orchestral instruments in two concert halls. In *Proceedings of the Third Vienna Talk on Musical Acoustics*, Vienna, Austria, Sep. 16-19, 2015.
18. H. Tahvanainen, J. Pätynen, and T. Lokki. Analysis of the seat-dip effect in twelve European concert halls. *Acta Acustica united with Acustica*, 101(4):731–742, 2015.
19. H. Tahvanainen, J. Pätynen, and T. Lokki. Studies on the perception of bass in four concert halls. *Psychomusicology: Music, Mind and Brain*, 2015.
20. D. Takahashi. Seat dip effect: The phenomena and mechanism. *Journal of the Acoustical Society of America*, 102(3):1326–1334, 1997.
21. A. Walther, P. Robinson, and O. Santala. Effect of spectral overlap on the echo threshold for single reflection conditions. *Journal of the Acoustical Society of America*, 134(2):EL158–EL164, 2013.